

AD A 117290

STANDARD
CLASSIFICATION

18 JUN 1982

HOLLENBAUGH

①

QUANTIFICATION OF HELICOPTER VIBRATION RIDE QUALITY USING ABSORBED POWER MEASUREMENTS

D. D. HOLLENBAUGH
APPLIED TECHNOLOGY LABORATORY
USARTL (AVRADCOM)
FORT EUSTIS, VIRGINIA 23604

INTRODUCTION

One of the concerns in helicopter design is the specification of acceptable vibration levels, mainly for the purpose of providing a reasonable work environment for the crew. In the multifrequency, multi-axis vibration environment of the helicopter, the determination of what is "acceptable" can be difficult. The accepted practice for many years has been the measurement and specification of vibration levels in terms of acceleration. This method is thoroughly documented in ISO 2631, "Guide for the Evaluation of Human Exposure to Whole-Body Vibration," (1) established by the International Organization for Standardization. This has come to be the standard reference for evaluation of vibrations. Even this thorough treatment has its limitations when applied to helicopters, as expressed by Kidd in a recent paper surveying the methods available for assessment of helicopter vibration (2).

In an effort to provide a more comprehensive method of evaluating helicopter ride quality, a preliminary investigation was conducted into the use for helicopter ride quality assessment of a ride quality assessment method developed for ground vehicles by the US Army Tank Automotive Command (TACOM) (3). This concept uses the amount of energy absorbed by the human body when subjected to vehicle vibrations as a measure of ride quality. Vibration measurements were taken on five US Army helicopters, and these vibration data were converted to absorbed power. This paper presents initial results of the investigation underway and describes plans for future research.

ABSORBED POWER

TACOM researchers, working from extensive ride simulator tests, first postulated that the perceived severity of a vibration is proportional to the rate at which the human body is absorbing energy. This energy absorption, referred to as absorbed power, is mathematically defined as:

DTIC
ELECTE
JUL 21 1982
B

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

82 07

19 261

page 1

DTIC FILE COPY

HOLLENBAUGH

$$P_{avg} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T F(t) V(t) dt$$

where P_{avg} = average power absorbed by the subject

$F(t)$ = input force on the subject

$V(t)$ = velocity of the subject

T = averaging time interval

If the input force is written as

$$F(t) = \sum_{i=0}^n F_i \sin(w_i t + \theta_i)$$

and the velocity as

$$V(t) = \sum_{i=0}^n V_i \sin w_i t$$

then the average power absorbed becomes

$$P_{avg} \sum_{i=0}^n \frac{G(jw_i) \sin \theta_i}{w_i} A_i^2 = \sum_{i=0}^n K_i A_i^2$$

where A_i = rms acceleration of the subject at frequency w_i

w_i = frequency of vibration

θ_i = phase angle between force and velocity

$G(jw_i)$ = Transfer function that relates force to acceleration

$G(jw) = F(jw)/A(jw)$

j = imaginary number, $j = \sqrt{-1}$

Note that the units of absorbed power are watts.

The transfer functions $G(jw)$ were developed for the three axes of whole-body vibration in extensive ride simulator tests and may be defined as body equivalent mass in each direction, for an average subject (male, 28 years, 150 pounds). Detailed information on these tests and the

Codes

Dist

Special

STAMP Security Classification
here

page 2

DTIC
COPY
INSPECTED
2

Insert last
page of report
here

HOLLENBAUGH

Stamp Security
Classification
here

Insert
first
page of
report
here

resulting transfer functions may be found in (4). The product of this extensive research is a model of vibration severity that correlates well with subjective response (5).

Insert
first
page type
title of
report here

Two points should be noted about absorbed power. First, it is a measurable scalar quantity, and absorbed power in different axes may be added to produce total absorbed power from multidegree of freedom vibrations. Secondly, it can be measured or calculated for periodic or random vibrations. An example of these two points will be shown later.

Author
Affiliation
City, State

Another interesting facet of absorbed power may be illustrated by conversion of the ISO data (1) into absorbed power, as shown in Figure 1. This is the ISO 8-hour fatigue/decreased proficiency boundary for vibration in the vertical direction. A large peak of absorbed power appears at 4-5 Hz. This large rise in absorbed power at an essentially constant acceleration is generally attributed to a resonating condition of the organs in the upper abdomen, with the diaphragm acting as a spring (6). A second, smaller peak appears around 12 Hz. This is believed to be caused by a resonating condition in the spinal column (6). These absorbed power peaks are due to the influence of the vertical body transfer function.

Insert line

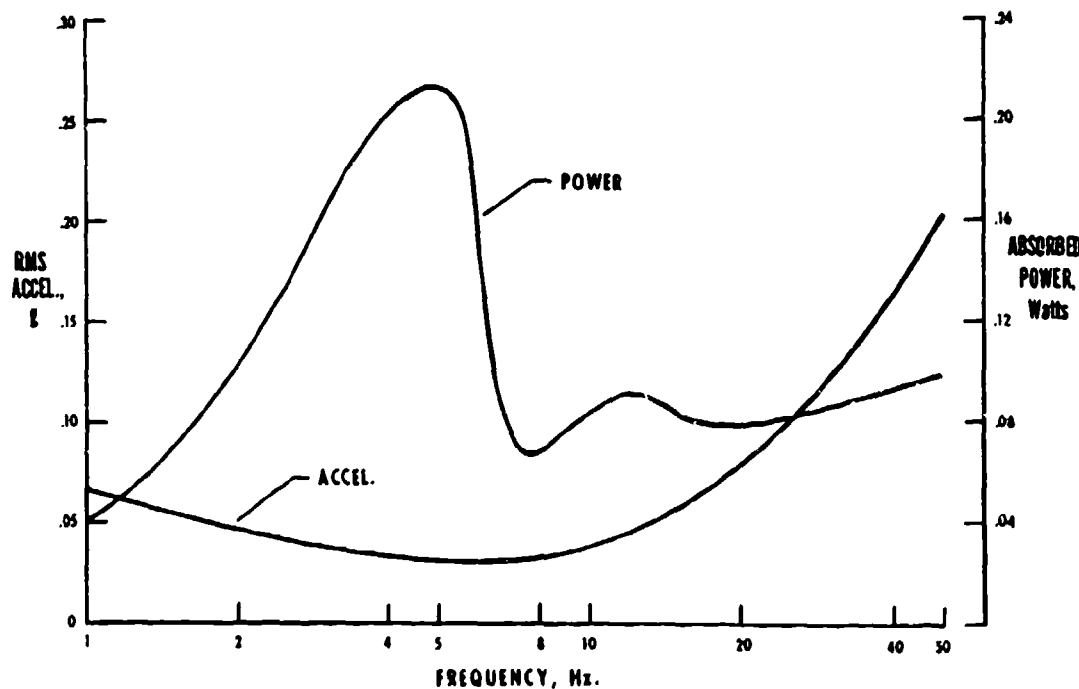


Fig. 1 - ISO 2631 8-hour fatigue/decreased proficiency boundary converted to absorbed power

Insert
first
page of
report only

Stamp Security Classification
here

HOLLENBAUGH

More to the point, it should be noted that these two frequency bands are primary regions of rotor-induced vibration for many helicopter designs, as can be seen in Table 1. Rotor-induced vibrations occur at the rotational speed of the main rotor (1 per revolution, or 1P), at the blade passage frequency (2P for a two-bladed rotor, 3P for a three-bladed rotor, etc.) and at the harmonics of the blade passage frequency.

Table 1. Significant frequencies for vibration considerations on helicopters tested

AIRCRAFT	1P	FREQUENCY, Hz				6P	8P
		2P	3P	4P			
CH-47C	3.9	-	11.8*	-		23.5	-
UH-60A	4.4	-	-	17.5*	-		35.1
UH-1H	5.4	10.8*	-	21.6	-		43.2
AH-1S	5.4	10.8*	-	21.6	-		43.2
OH-58C	5.9	11.8*	-	23.6	-		47.2

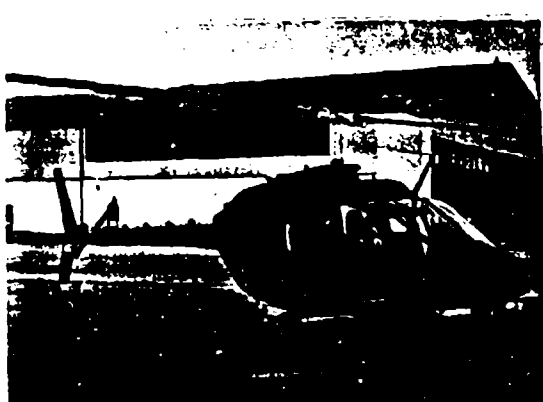
*Blade passage frequency

MEASUREMENTS

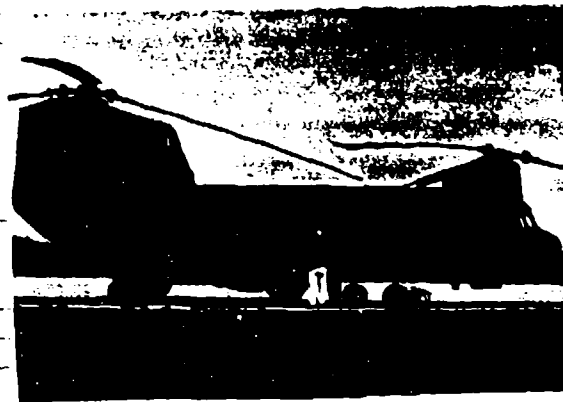
The test aircraft chosen for this investigation were representative of each helicopter type presently in use by the active US Army. Included were a Bell UH-1H Iroquois, a Bell OH-58C Kiowa, a Bell AH-1S modernized TOW Cobra, a Boeing Vertol CH-47C Chinook, and a Sikorsky UH-60A Blackhawk. Aircraft and flight crews were provided by the Aviation Maintenance Management Training Division of the US Army Transportation School, Fort Eustis, Virginia. These aircraft are shown in Figure 2. It should be pointed out that these were operational fleet aircraft, and only one example of each type, in one configuration, was flown for measurements. Therefore, the data shown should not be taken as a thorough vibration survey of any of the aircraft types.

Two sets of instrumentation were carried on board each test flight. The first consisted of a triaxial accelerometer package linked to a seven channel analog tape recorder for recording vibration levels. The second set consisted of an acoustical tape recorder and two microphones for recording aircraft internal noise. All instrumentation was provided by NASA-Langley Research Center.

HOLLENBAUGH



(a) OH-58C



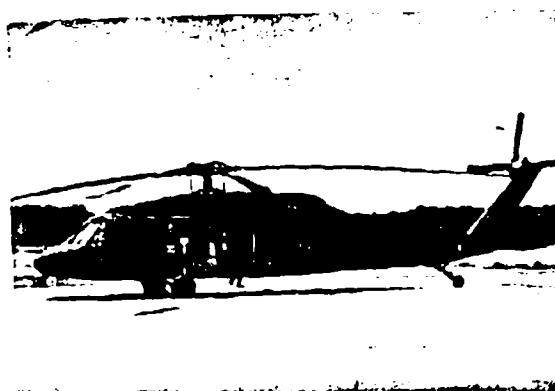
(b) CH-47C



(c) UH-1H



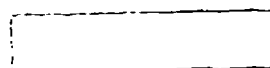
(d) AH-1S



(e) UH-60A

Fig 2. - Test aircraft for absorbed power measurements

STAMP Security Classification
here



HOLLENBAUGH

The accelerometer package was placed as close as possible to the base of the aircraft pilot's seat. The acoustical microphones were placed near the pilot's and copilot's heads. Vibration and sound recordings were then taken for a period of roughly 30 seconds at each of the following conditions: hover in ground effect (IGE), hover out of ground effect (OGE), rearward flight, left and right sideward flight, standard climb at cruise velocity, and forward flight at speeds from 10 knots to maximum level flight speed.

It was originally intended that absorbed power measurements would be made directly from the vibration recordings, using an instrument developed by TACOM for that purpose (6). However, during the data reduction process it was discovered that the instrument electronics were optimized for the vibration levels and frequencies characteristic of ground vehicles, and, as a result, the instrument proved inaccurate for absorbed power measurements on helicopter vibration. Therefore, the absorbed power measurements were obtained from the recorded vibrations using a computer implementation of the absorbed power equations.

RESULTS AND DISCUSSION

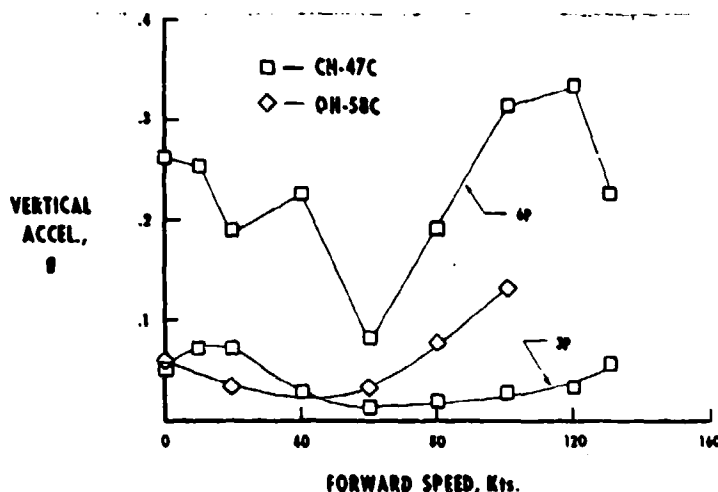
The vertical acceleration levels measured on test aircraft are shown as a function of forward flight speed in Figure 3a and 3b. The data shown are peak amplitude at blade passage frequency, which is shown in Table 1. This is normally the highest vibration level in the helicopter spectrum. In the case of the CH-47C, the blade passage frequency (3P) and its second harmonic (6P) are shown to display the dominance of the second harmonic in this particular type.

These data are shown to indicate the general trend of vibration with airspeed, which came out as expected. It also shows the wide variation of vibration level between aircraft types. Once again, it should be remembered that these data are for a particular aircraft on a particular day, to determine general trends, and data on a particular aircraft should not necessarily be taken as representative in a statistical sense of the type.

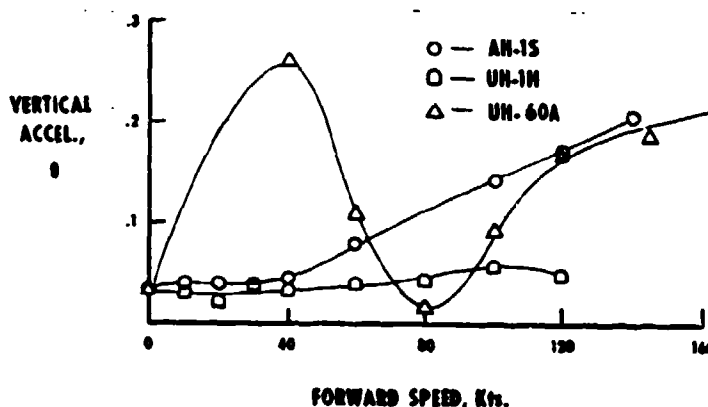
STAMP Security Classification
here

HOLLENBAUGH

STAMP Security
Classification
here



(a)



(b)

Fig. 3(a) & (b) - Variation of vertical vibration with airspeed

The evolution of a particular absorbed power data point is shown in Figures 4-6. It begins with a Fourier transform of the raw acceleration data, a portion of which is shown in Figure 4. This is the vertical acceleration data recorded on an AH-1S in forward flight at 135 knots. Only the portion from 0-40 Hz is shown but, as will be shown, this is the most important area. Figure 5 is a vibration spectral density plot, which pinpoints the major vibratory frequencies and vibration levels.

STAMP Security Classification
here

HOLLENBAUGH

The clearly dominant vibration, at 10.5 Hz, is the main rotor blade passage frequency (2P). It is interesting to compare Figure 5 with the absorbed power density graph of Figure 6. Figure 6 is created by multiplying Figure 5 by the vertical transfer function. Here the effect of the body transfer function can be fully appreciated. The low vibration level at 5.4 Hz (1P) becomes a major producer of absorbed power, while the higher vibration levels at 1 Hz and at 20 Hz become relatively less important. Also, any vibration above 30 Hz becomes almost negligible when expressed as absorbed power. This graph is then integrated to produce an absorbed power number, which in this case is .624. By this method both periodic and random vibration at all frequencies are taken into account, properly weighted and quantified by a single ride quality (absorbed power) number.

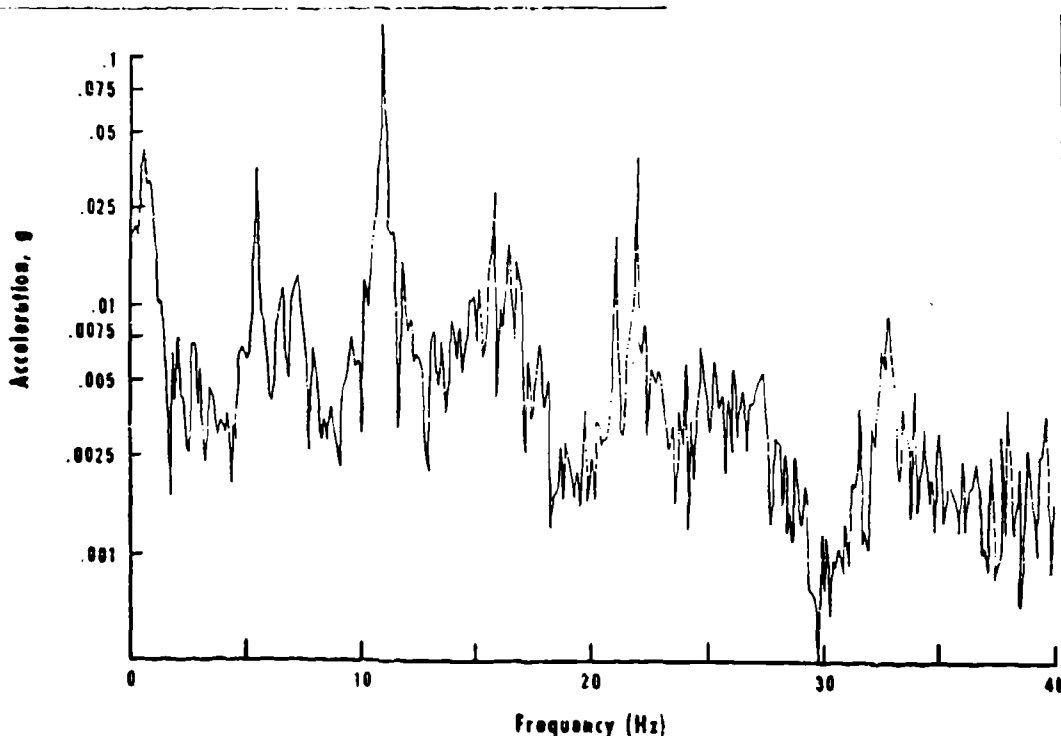
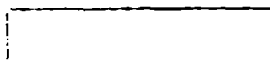


Fig. 4 - Vertical acceleration levels vs frequency, AH-1S, 135 knots

STAMP Security Classification
here



Document Number

Document Title

Document Date

Document Type

Document Status

Document Source

Document Location

Document Access

Document Control

Document History

Document Revision

Document Change

Document Approval

Document Signature

Document Date

Document Location

Document Access

Document Control

Document History

Document Revision

Document Change

Document Approval

Document Signature

Document Date

Document Location

Document Access

Document Control

Document History

Document Revision

Document Change

Document Approval

Document Signature

Document Date

Document Location

Document Access

Document Control

Document History

Document Revision

Document Change

Document Approval

Document Signature

Document Date

Document Location

Document Access

Document Control

Document History

Document Revision

Document Change

Document Approval

Document Signature

Document Date

Document Location

Document Access

Document Control

Document History

Document Revision

Document Change

Document Approval

Document Signature

Document Date

Document Location

Document Access

Document Control

Document History

HOLLENBAUGH

STAMP Security Classification here

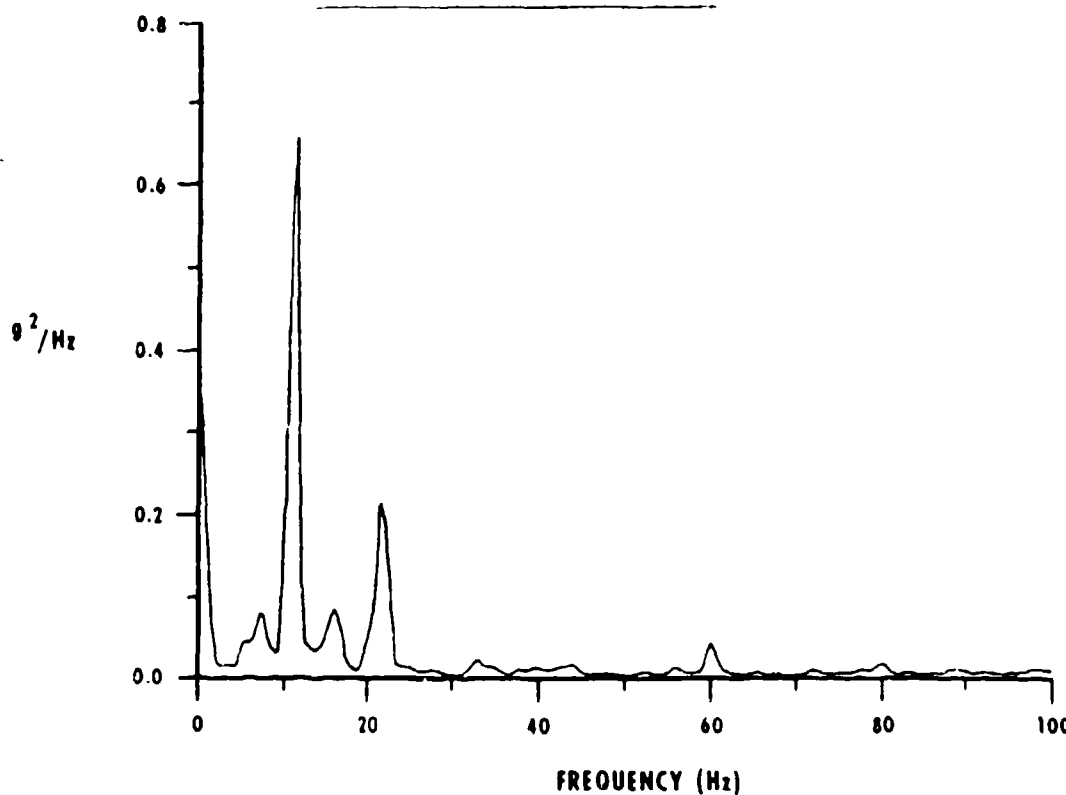


Fig. 5 - Power spectral density, vertical axis, AH-1S, 135 knots

STAMP
downgrading/
declassification
information
on first
page of
paper only

STAMP Security Classification here

HOLLENBAUGH

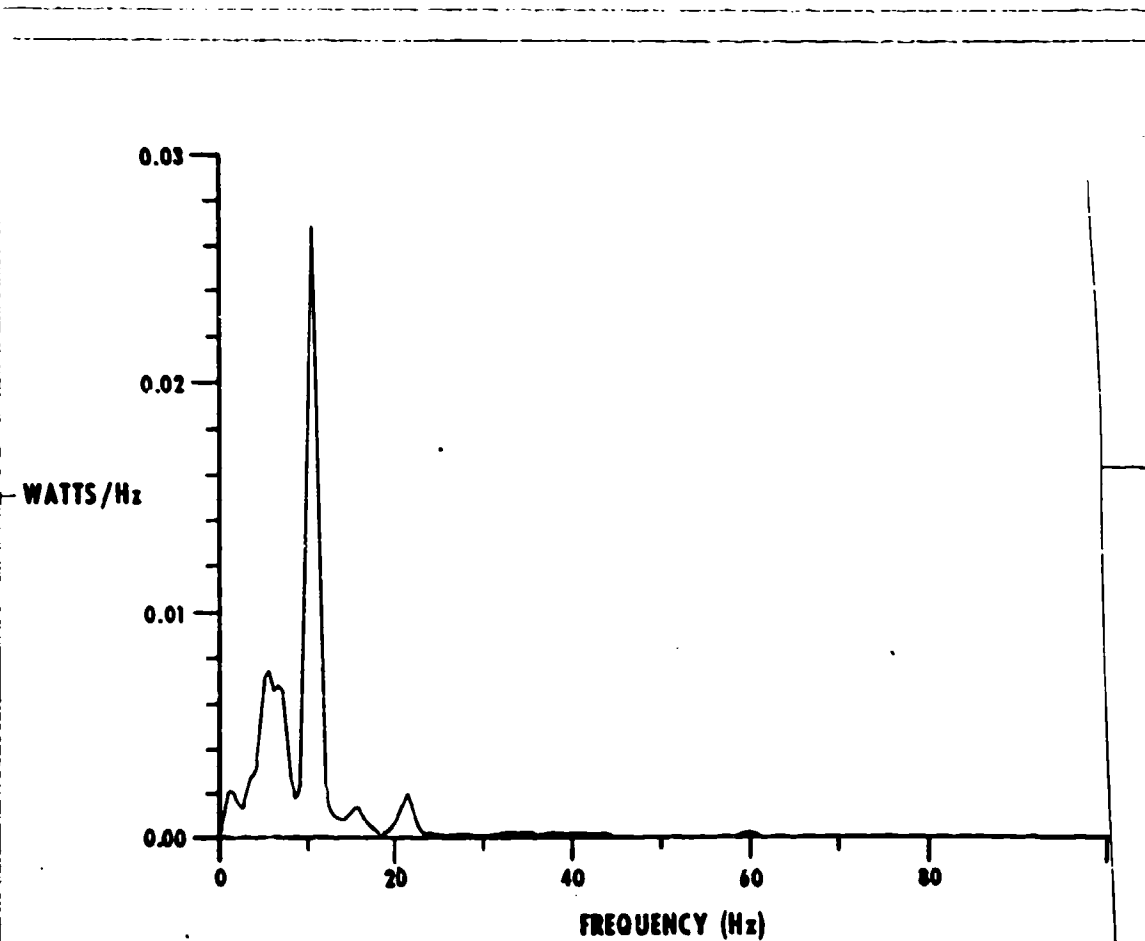


Fig. 6 - Absorbed power density, vertical axis, AH-1S, 135 knots

The collected absorbed power data is shown versus airspeed in Figures 7-9 for vertical, fore-aft and side-to-side axes, and in Figure 10 the three axes are summed to produce total absorbed power versus airspeed. The points shown for 0 airspeed are hover IGE. It can be seen that the side-to-side and fore-aft absorbed power levels are generally lower than the absorbed power levels from vertical vibrations. This can be attributed to the fact that measured vibration levels in these directions are generally lower, and to the transfer functions, which show less body vibration response in the fore-aft and side-to-side

STAMP Security Classification
here

HOLLENBAUGH

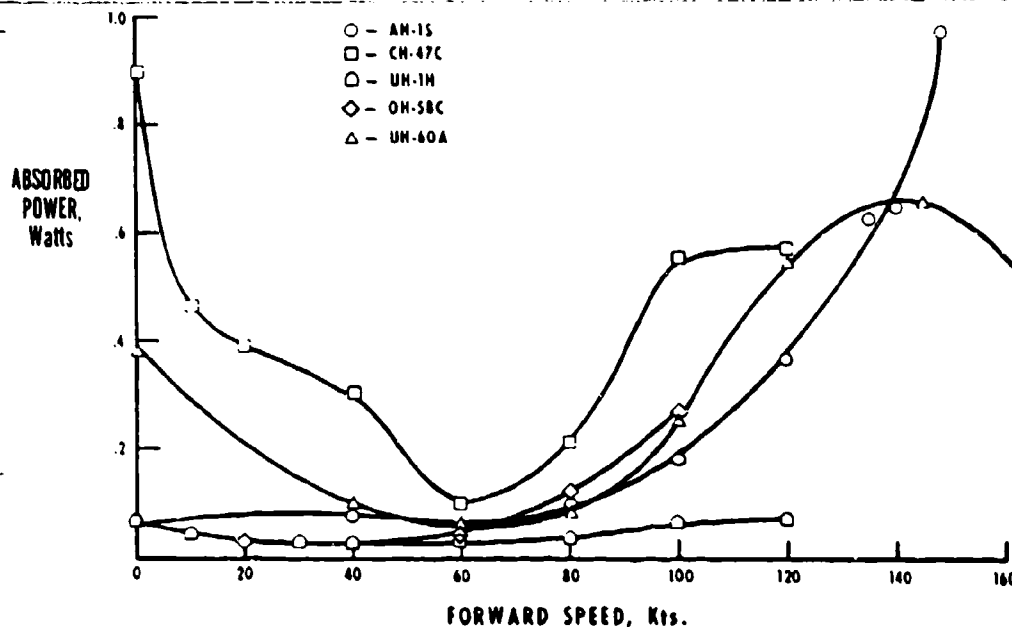


Fig. 7 - Absorbed power from vertical acceleration vs airspeed

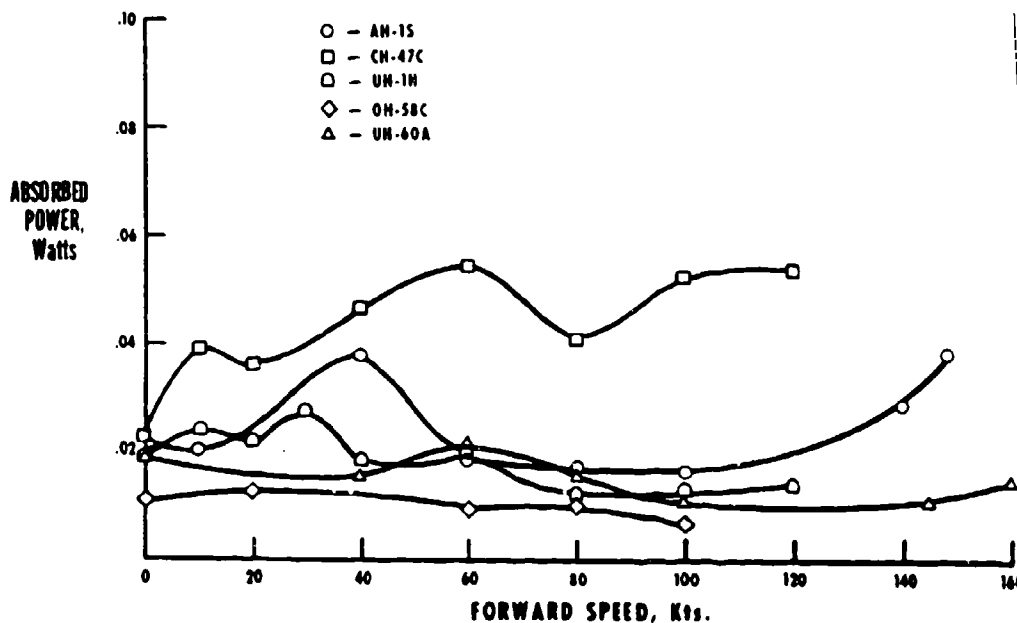
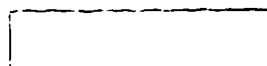


Fig. 8 - Absorbed power from fore-aft acceleration vs airspeed

STAMP Security Classification
here.



HOLLENBAUGH

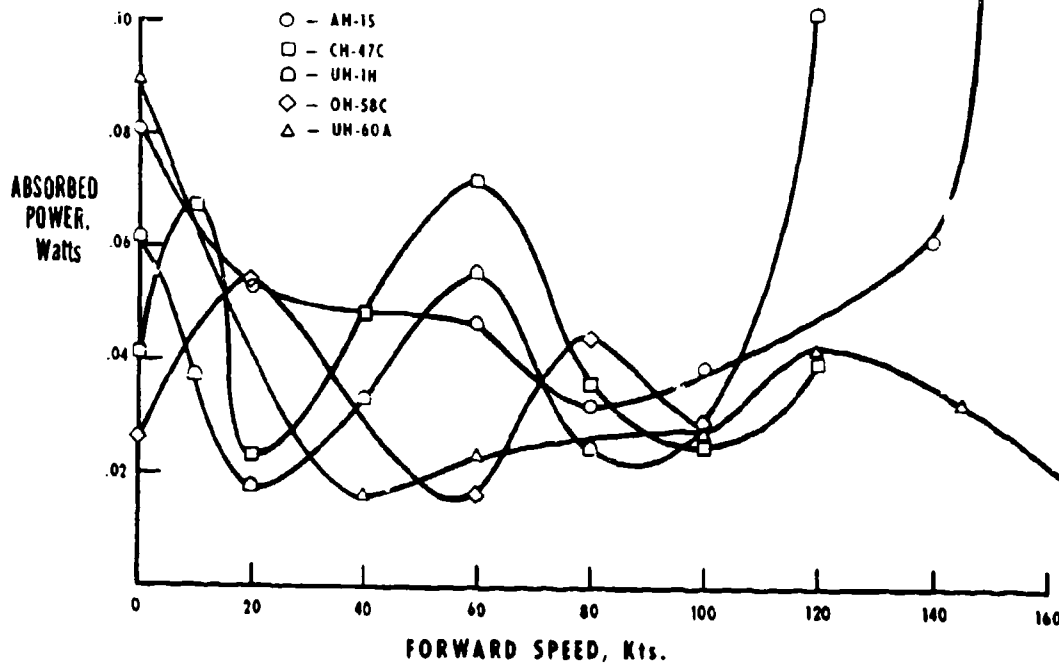


Fig. 9 - Absorbed power from side-to-side acceleration vs airspeed

Stamp Security Classification
here

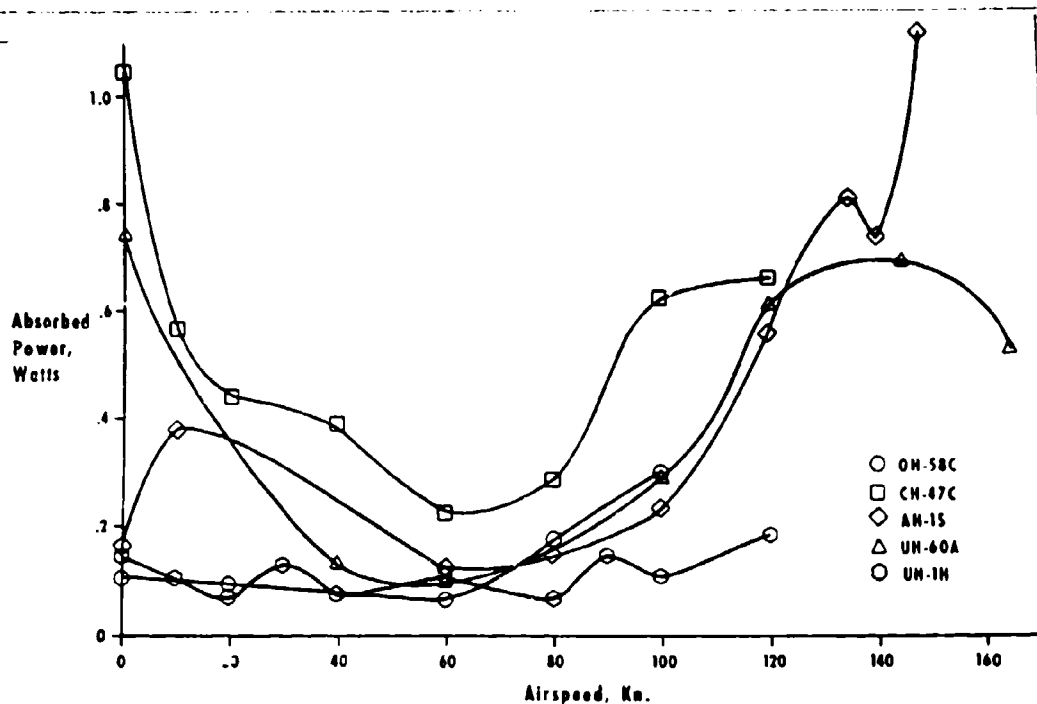


Fig. 10 - Total absorbed power vs airspeed

axes. There is an exception to the dominance of the vertical, however, and it illustrates a further strength of the absorbed power concept. Figures 11 and 12 show the relative contributions to absorbed power of vibration in the three axes for two of the aircraft tested. In the case of the UH-60A the fore-aft and side-to-side are relatively minor, and the fore-aft is essentially constant with airspeed. For the AH-1S the fore-aft contribution is larger than for the UH-60A and fluctuates with airspeed, and the side-to-side component contributes a much larger percentage of total absorbed power than in the case of the UH-60A. This can be explained by an examination of the designs of the two rotor systems. The UH-60A uses a fully articulated rotor, with lead-lag and flapping hinges and a pitch bearing on each blade, while the AH-1S has only a pitch bearing. Without lead-lag and flapping hinges to alleviate in-plane rotor induced vibrations, this vibration is transferred to the aircraft. Thorough study of all the absorbed power data showed this difference in relative contributions to absorbed power of the three axes due to rotor system design to be the trend. This ability of the absorbed power concept to properly weigh and integrate the various axes of vibration in this manner is viewed as another strength of the concept.

STAMP Security Classification
here

STAMP Security
Classification
here

HOLLENBACH

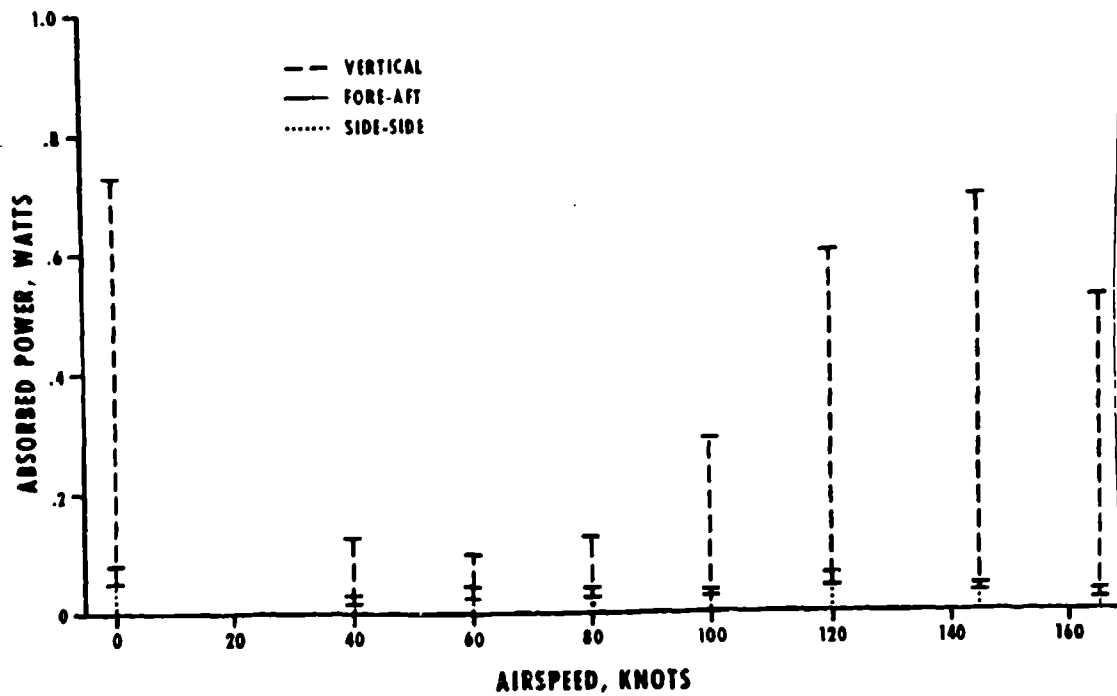


Fig. 11 - Relative contributions of absorbed power in three axes vs airspeed - UH-60A

STAMP Security Classification
here

Stamp Security Classification here

HOLLENBAUGH

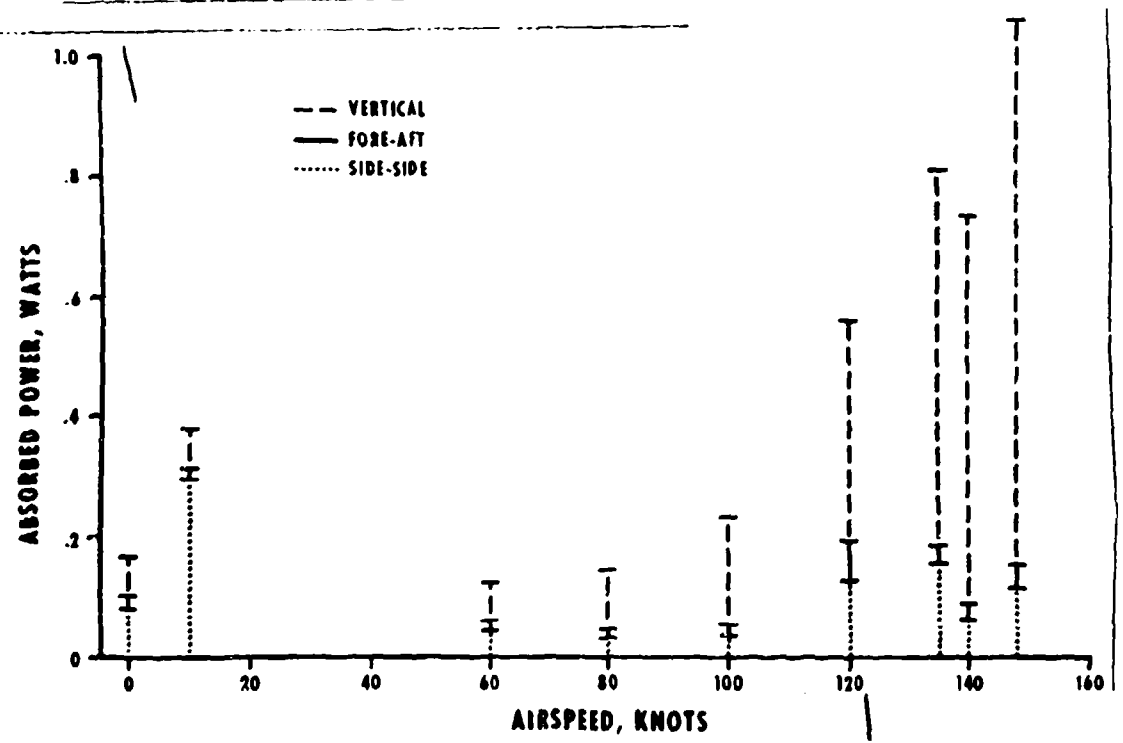


Fig. 12 - Relative contributions of absorbed power in three axes vs airspeed - AH-1S

Stamp Security Classification here

HOLLENBAUGH

SUBJECTIVE RESPONSE EXPERIMENTS

Currently underway is a program to correlate the collected absorbed power data with subjective response data, to aid in determining the validity of the absorbed power model for rotorcraft. The apparatus used to conduct these experiments is the Passenger Ride Quality Apparatus (PRQA) at NASA-Langley Research Center (Figure 13). The PRQA is a three-axis hydraulically driven motion simulator configured as a portion of an airliner cabin. A thorough description of the PRQA is given in (7). The PRQA is equipped with four airline-type seats and speakers for repeating recorded aircraft sounds. For the purpose of this experiment, the recorded noise and vibration data for hover IGE and forward flight at normal cruise velocity in each of the five Army aircraft are used. Noise levels are lowered using attenuation levels for the standard SPH-4 Army flight helmet (8). To produce various combinations of noise and vibration levels, noise levels are played with SPH-4 helmet attenuation, reduced by 7 dB, reduced by 14 dB, and eliminated altogether. Vibration levels are played as recorded, reduced by 3 dB, and by 9 dB. All different combinations of noise and vibration levels are run for each of the ten ride segments, producing 120 data points.

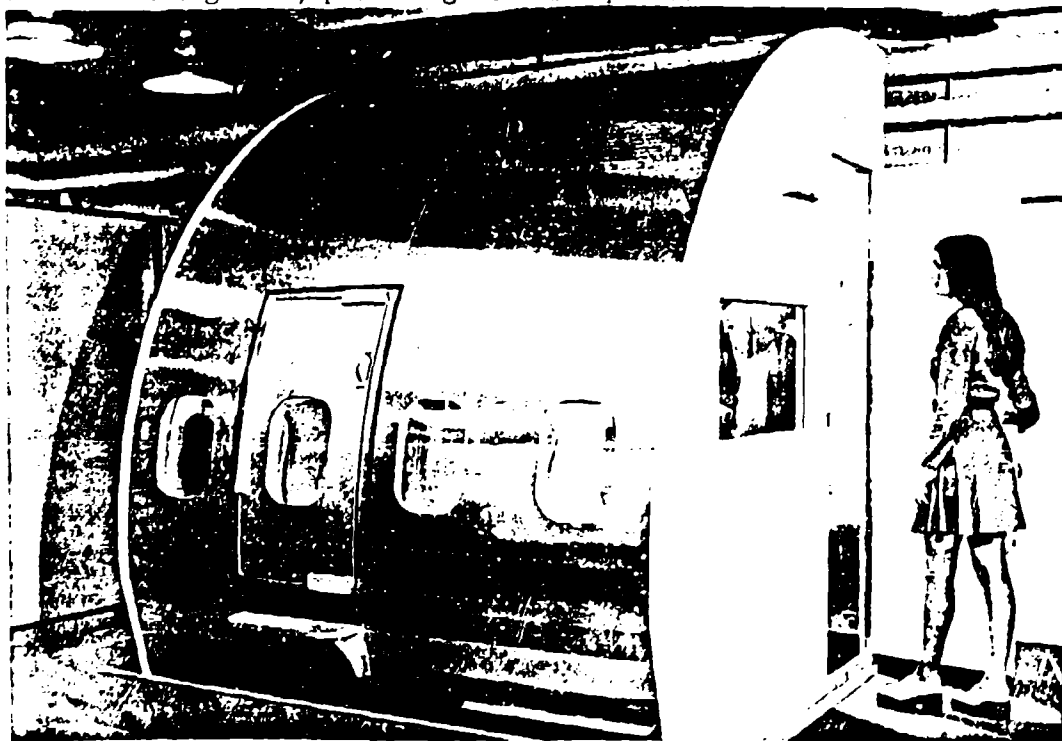
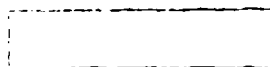


Fig. 13 - NASA Passenger Ride Quality Apparatus (PRQA)

STAMP Security Classification
here



HOLLENBAUGH

The purpose of varying noise levels is to provide subjective response data for comparison with the NASA-Langley Ride Comfort Model. This is an empirical model which determines ride quality as a function of vibration and noise levels. In concert with the evaluation of absorbed power described in this paper, NASA-Langley researchers are studying the applicability of the NASA Ride Comfort Model to rotary wing aircraft. The results of this effort up to this time are covered in (9). For each of the 120 data points, the test subjects, Army and Navy helicopter pilots, rate each ride segment on a comfort scale. As of this writing, too little data has been produced to draw any conclusions.

CONCLUDING REMARKS

The absorbed power concept offers certain advantages over pure acceleration for helicopter ride quality evaluation. First, it takes into account multi-frequency, multi-axial vibration across a broad frequency range. Second, it provides proper weighting functions for all frequencies and axes according to body response. Third, it is applicable to random as well as periodic accelerations.

A larger data base and further experimentation is required for full validation of absorbed power as a means for quantifying helicopter vibration ride quality. Further in-flight data will be collected to expand the vibration/noise environment data base, repeating measurements on the aircraft mentioned here, and add further aircraft. Already underway is a program to take measurements on US Navy aircraft types. Data have been recorded on a Sikorsky RH-53D and a Kaman SH-2F. The subjective response experiments will be continued for correlation and validation of the absorbed power and NASA Ride Comfort Model.

REFERENCES

1. Anon., "Guide for the Evaluation of Human Exposure to Whole-Body Vibration," International Standard ISO 2631, 1978.
2. Kidd, D. L., "Assessment of Helicopter Vibration Criteria," American Helicopter Society Preprint 81-22, 37th Annual Forum of the American Helicopter Society, New Orleans, Louisiana, May 1981.
3. Lee, R. A. and Pradko, F., "Analytical Analysis of Human Vibration," Society of Automotive Engineering Congress, Detroit, Michigan, January 1968.
4. Lins, W. F., "Human Vibration Response Measurement," US Army Tank-Automotive Research and Development Command Technical Report 11551, June 1972.

STAMP Security Classification
here

Insert last
line of au-
thor(s) here

HOLLENBAUGH

Part were
for all
pages
after the
first

5. Pradko, F., Lee, R. A., Greene, J. D., "Human Vibration Response Theory," American Society of Mechanical Engineers, Paper 75-WA/HUF-19, Winter Annual Meeting, Chicago, Illinois, November 1965.

On first
page type
title of
paper here

6. Lee R. A., Cumbow, J., "Absorbed Power Ride Measurement Instrument," US Army Tank-Automotive Research and Development Command Technical Report 12415, December 1978.

Author
Affiliation
City, State

7. Stephens, D. G., Clevenson, S. A., "The Measurement and Simulation of Vibration for Passenger Ride Quality Studies," Proceedings of the Technical Program, National Noise and Vibration Control Conference, 1974.

First line

8. Megehee, J. H., "Service Tests of SPH-4 Protective Helmet," Army Aviation Test Board, Fort Rucker, Alabama, September 1969.

9. Hammond, C. E., Hollenbaugh, D. D., Clevenson, S. A., Leatherwood, J. D., "An Evaluation of Helicopter Noise and Vibration Ride Qualities Criteria," presented at American Helicopter Society Northeast Region Specialist's Meeting on Helicopter Vibration, Hartford, Connecticut, November 1981.

Stamp
downgrading/
declassification
information
on first
page of
paper only

STAMP Security Classification
here